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The Course-Of-Action Selection Tool (COAST) was developed at NRaD to support the preparation of a Course-of-Action (COA) Selection Matrix by the Operational Planning Team (OPT) at USPACOM. The COA Selection Matrix is used to brief a recommended COA and alternative COAs for a proposed mission to the CINC.

The COA Selection Matrix currently used at USPACOM employs a weighted-sum method for evaluating COAs against a set of selection criteria. It consists of a matrix of scores, where each column in the matrix represents the evaluation of a COA against the criteria. Each criterion is given a multiplicative weighting factor according to its importance. The sum of these weighted scores determines the recommended COA.

The primary benefits of the weighted-sum method are simplicity and clear identification of the advantages of the COA. These benefits diminish if it is desired to attach additional meaning to the specific numbers in the matrix. In particular, relative risk between criteria is not represented well and overall mission risk is not represented at all. The weighted-sum does not consider whether there is dependence among criteria. More importantly, different missions with different criteria cannot be compared, whether for concurrent evaluation or historical analysis, because the weighted-sum is not a normalized measure of success.

COAST addresses these concerns by using results from decision theory [Larsen and Dillard] to provide a decision support methodology that produces a briefing product like the COA Selection Matrix currently in use, but represents an improvement both in terms of theoretical basis and COA option presentation. Like the weighted-sum, COAST solves multiple criteria decision problems when the criteria have differing degrees of importance. But more importantly, an enhancement due to [Yager] and [Zadeh and Bellman] uses probability and fuzzy logic to combine the risk and importance associated with each criterion to estimate overall probability of mission success.

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Course-Of-Action Selection Tool
COAST

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OVERVIEW

The Course-Of-Action Selection Tool (COAST) was developed at NRaD to support the preparation of a Course-of-Action (COA) Selection Matrix by the Operational Planning Team (OPT) at USPACOM. The COA Selection Matrix is used to brief a recommended COA and alternative COAs for a proposed mission to the CINC.

The COA Selection Matrix currently used at USPACOM employs a weighted-sum method for evaluating COAs against a set of selection criteria. It consists of a matrix of scores, where each column in the matrix represents the evaluation of a COA against the criteria. Each criterion is given a multiplicative weighting factor according to its importance. The sum of these weighted scores determines the recommended COA.

The primary benefits of the weighted-sum method are simplicity and clear identification of the advantages of the COA. These benefits diminish if it is desired to attach additional meaning to the specific numbers in the matrix. In particular, relative risk between criteria is not represented well and overall mission risk is not represented at all. The weighted-sum does not consider whether there is dependence among criteria. More importantly, different missions with different criteria cannot be compared, whether for concurrent evaluation or historical analysis, because the weighted-sum is not a normalized measure of success.

COAST addresses these concerns by using results from decision theory [Larsen & Dillard] to provide a decision support methodology that produces a briefing product like the COA Selection Matrix currently in use, but represents an improvement both in terms of theoretical basis and COA option presentation. Like the weighted-sum, COAST solves multiple criteria decision problems when the criteria have differing degrees of importance. But more importantly, an enhancement due to [Yager] and [Zadeh and Bellman] uses probability and fuzzy logic to combine the risk and importance associated with each criterion to estimate overall probability of mission success.

The inputs to COAST are (1) a set of COAs, (2) a set of criteria, (3) a comparison of the importance of the criteria, and (4) the degree to which each COA satisfies each criterion. The evaluation criteria can be entered manually or selected from a library of criteria listed by category. The categories used in COAST are derived from the Principles of War found in [Clausewitz] and other sources. Criteria such as initiative, mass, and flexibility are used to evaluate the COAs. Once the user selects the evaluation criteria, the importance of each criterion to the mission is determined. After an initial ranking of the criteria, a pairwise comparison can be made to verify and refine the rankings using techniques developed by [Saaty]. The consistency of the pairwise ranking is measured and inconsistent pairs are automatically recognized and identified to the user.

After the criteria are ranked by importance, the user evaluates the degree each COA satisfies each criterion. This is accomplished using probabilistic language (certain, probable, likely, possible, unlikely, doubtful). Fuzzy logic is then used to combine the importance of each criterion with the probability the criterion is met to compute a probabilistic measure of the impact of each criterion on success. If a criterion is less than essential, its impact on mission success is reduced. That is, the probability of the mission satisfying a criterion is increased if the criterion is less than essential to the mission. (This is essentially equivalent to giving a criterion less weighting in the weighted-sum method.) The results are presented as a COA Selection Matrix. Compared with the COA Selection Matrix currently in use, this technique clearly identifies in probabalistic terms the highest risk criterion for each COA.

An overall probability of mission success can be computed by combining the probabilities of satisfying the individual criterion. If the dependence between criterion is known, it can be accommodated in a probabilistic combination calculation. A more important issue is to decide what is meant by the probability of mission success in the context of satisfying selection criteria. Should it be the probability that "all criteria are met"? After some consideration, it was decided the probability that "most criteria are met" is the preferred measure, primarily because it has properties similar to the weighted-sum currently in use. To this end, the mean of the individual probabilities for the set of criteria was found to be a good approximation to the probability that "most criteria are met". The standard deviation of the individual probabilities about their mean is used to determine the statistical significance of mean probability differences between COAs. In this way, not only the ranking, but also the significance of the ranking of the COAs is determined. The result is a measure of the probability of mission success. It is also an indication of risk in the sense that the probability of mission failure is the complement of the probability of mission success. More importantly, probability of mission success is a normalized estimate which can be used to meaningfully compare different missions with different evaluation criteria.

USER INTERFACE

The user interface for COAST was originally written in Hypercard for the Macintosh. Subsequently it was converted to Metacard for the SUN workstation version which is illustrated here. Both versions use color. Unfortunately, the grey scale reproductions here do not illustrate the use of color. Figure 1 is the **Title** card for COAST. There are 5 buttons in the top menu bar, **Quit**, **Setup**, **Clear**, **Help** and **Start**.

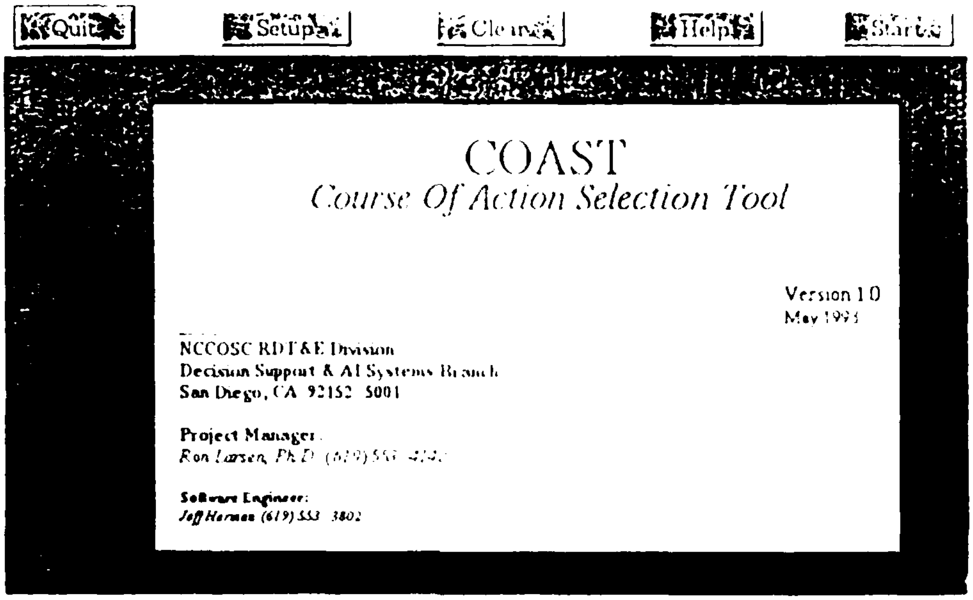

Fig. 1. **Title** Card

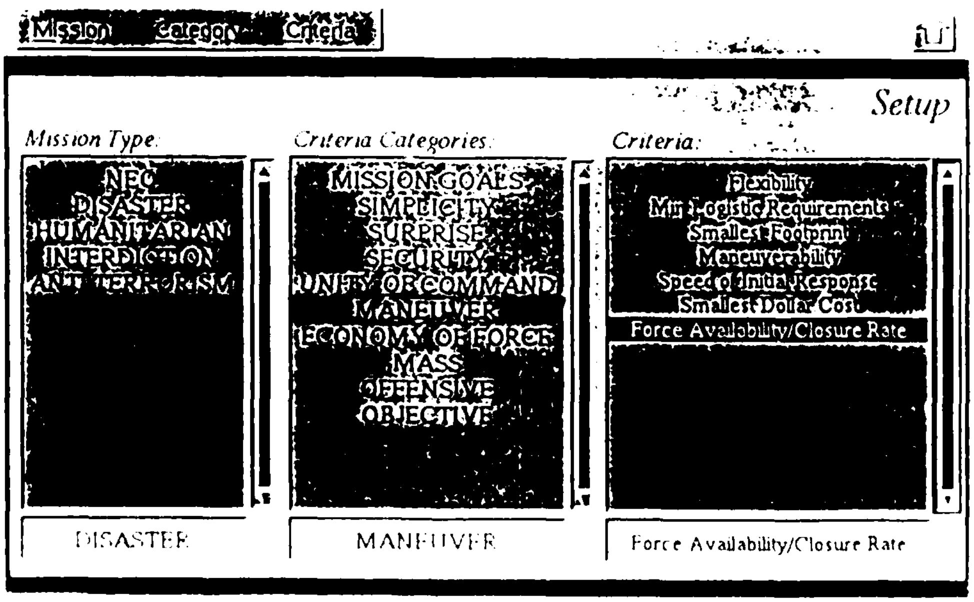

Fig. 2. **Setup** Card

Selecting **Setup** brings us to the card shown in Figure 2. This card allows the user to set up a library of criteria and their categories for each mission type. In the example, the user has added the criterion *Force Availability/Closure Rate* to the MANUEVER category for a DISASTER mission type.

Selecting the up arrow in the upper right hand corner of the **Setup** card brings us back to the **Title** card. Selecting **Clear** resets all cards in order to start a mission evaluation from the beginning. The user now begins by selecting **Start** from the **Title** card. This brings us to the **List COA** card which is shown in Figure 3. The user enters the name of the mission, Bangladesh Relief, selects the mission type, in this case DISASTER, and lists the COAs. Three COAs have been listed.

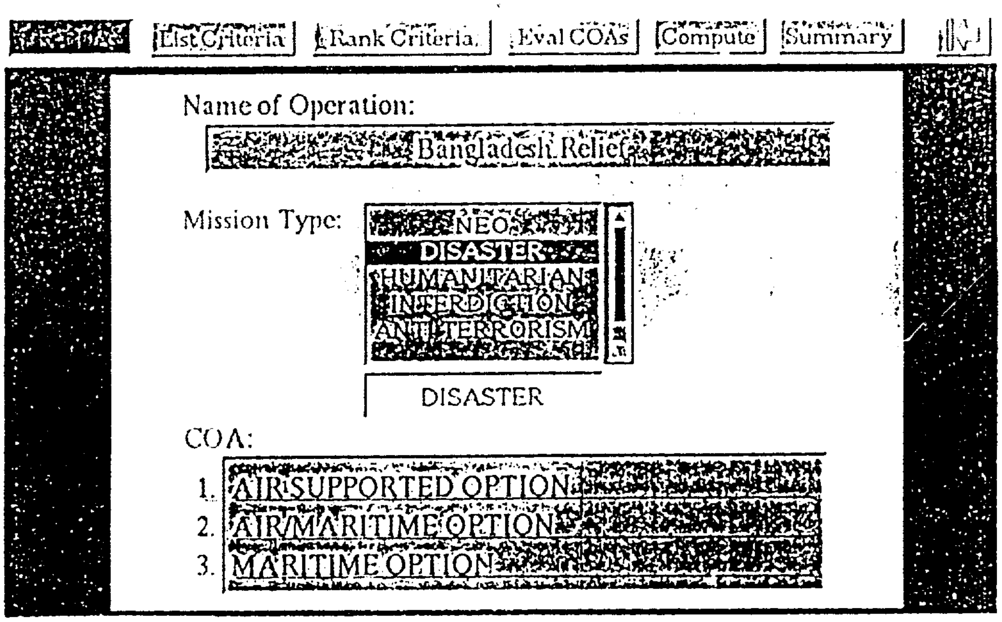

Fig. 3. **List COA** Card

Next, the user selects **List Criteria** from the menu bar (Figure 4). Ten criteria to be used to evaluate the COAs have been entered. They can be selected from the criteria library, typed in manually or ported in from an external planning aid. In the example shown, the tenth criterion, *Force Availability/Closure Rate*, has been selected from the Criteria Library as shown on the right side of the card.

The next step, **Rank Criteria**, is shown in Figure 5. The initial ranking is accomplished by selecting one of the three Importance Measures from the menu in the lower right hand corner. In this case one criterion is rated *essential* (a score of 3), two are rated *very important* (a score of 2), and 7 are rated *important* (a score of 1). If the rated critera were not in order of importance, the **Sort** button takes care

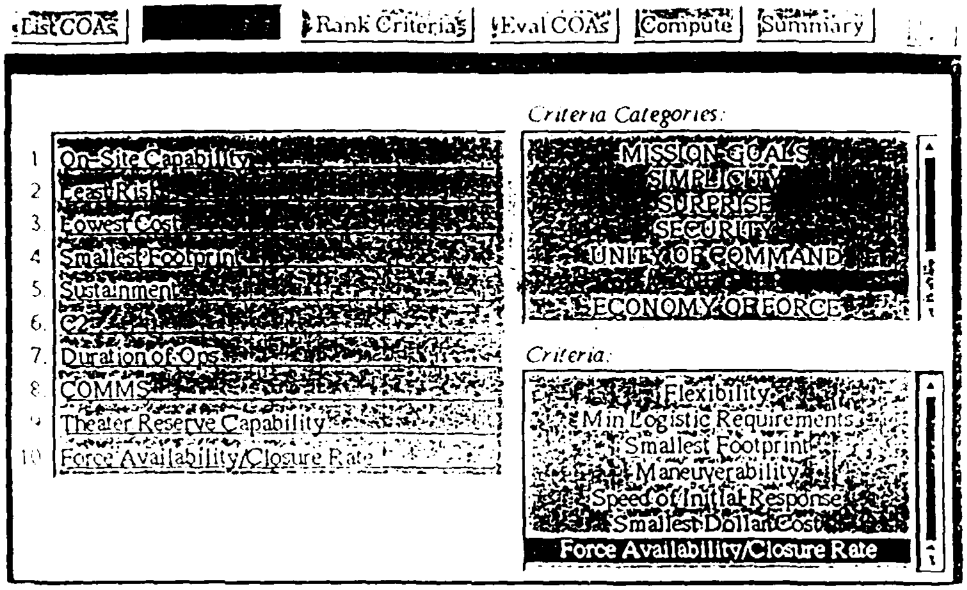

Fig. 4. **List Criteria Card**

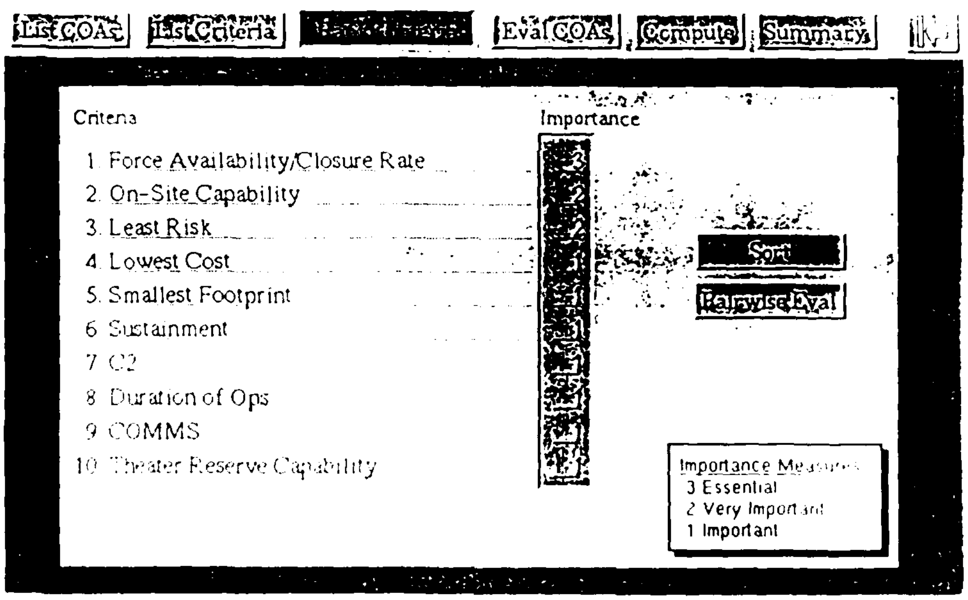

Fig. 5. **Rank Criteria Card**

of it. The Pairwise Evaluation button may be used to verify the rank scores. Figure 6 shows a comparison being made for two criteria. In the example, *Force Availability/Closure Rate* is rated to have *Some Importance* (a score of 1) over *Least Risk*. Once the pairwise comparisons are done, the user is shown a summary **Pairwise Evaluation** card, Figure 7. As can be seen, the user requested an evaluation of the top four criteria and the six resulting pairwise comparisons are shown. In this case the consistency of the pairwise rankings is rated OK, as seen

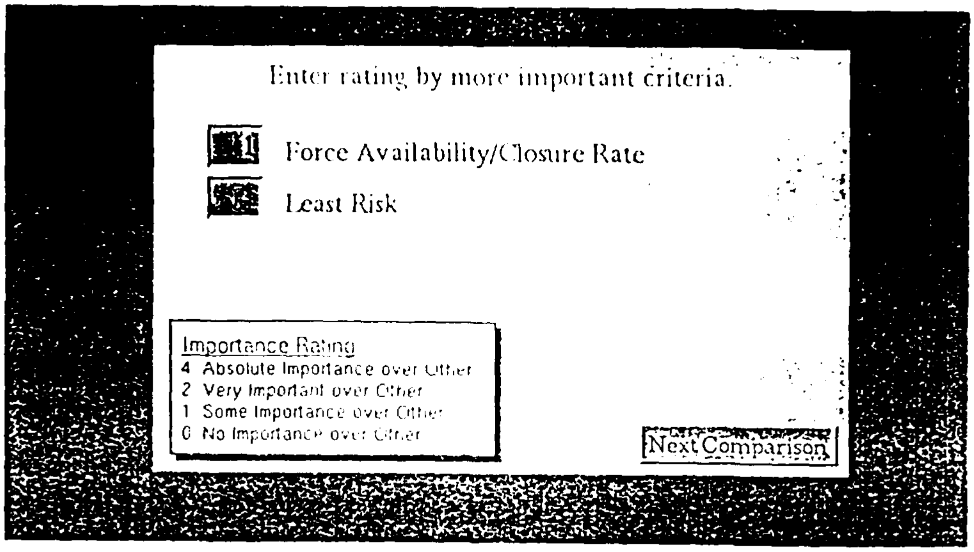

Fig. 6. **Pairwise Comparison Card**

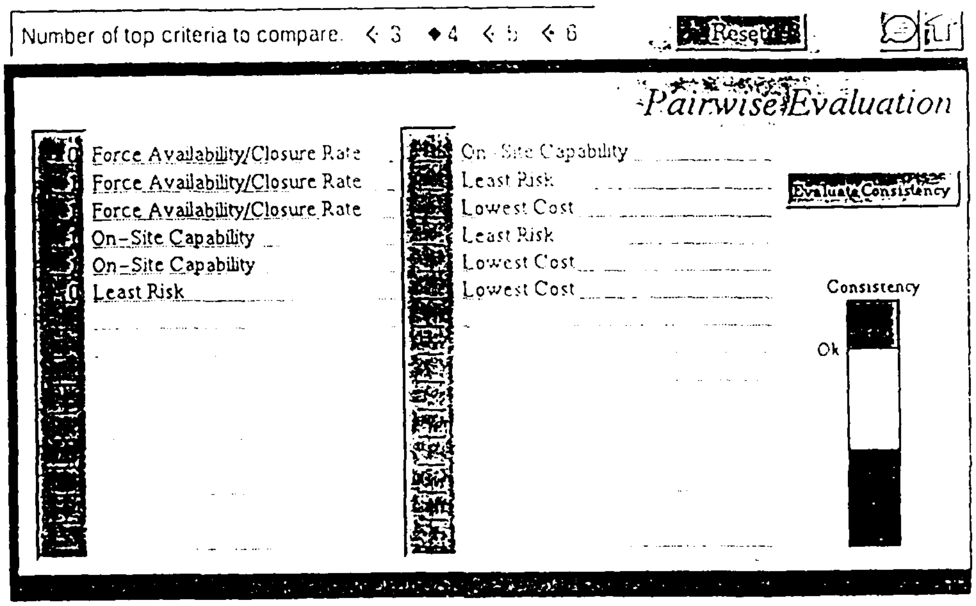

Fig. 7. **Pairwise Evaluation Card**

on the barometer on the right. If the pairwise rankings had not been consistent, the pair causing the greatest discrepancy would have been identified to the user. "Fixing" discrepancies is discretionary because they do not invalidate the results. Next we return to the **Rank Criteria** card, Figure 8, where the original ranking (**Old**) and pairwise ranking (**New**) are shown. In this case we will **Make Change** to the **New** numbers, Figure 9.

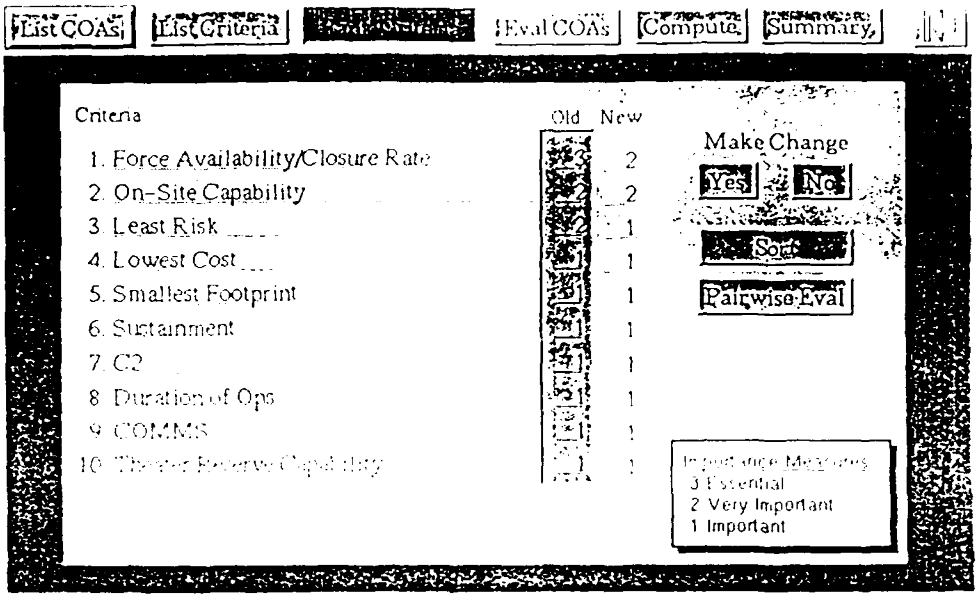

Fig. 8. **Old** vice New **Rank Criteria** Card

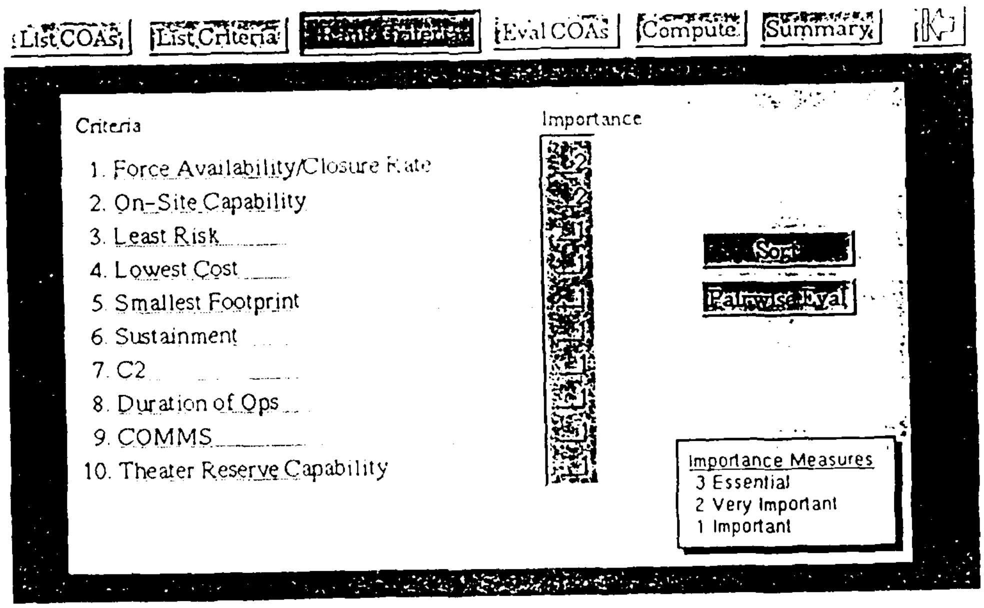

Fig. 9. Final **Rank Criteria** Card

Next, we select the **Evaluate COAs** card, Figure 10. The three COAs are listed against the criteria. The user evaluates the degree to which each COA satisfies each criterion using the **Degree Criteria Met** menu of eight probabalistic terms which range from **Certain** to **No Chance**. The terms are numerically and color coded. The numerical values are probabilities used in fuzzy computations. The **Hide Colors** and **Hide Scores** buttons give users the option of what they see. Hiding colors and scores until the evaluation process is complete assists in making unbiased judgements.

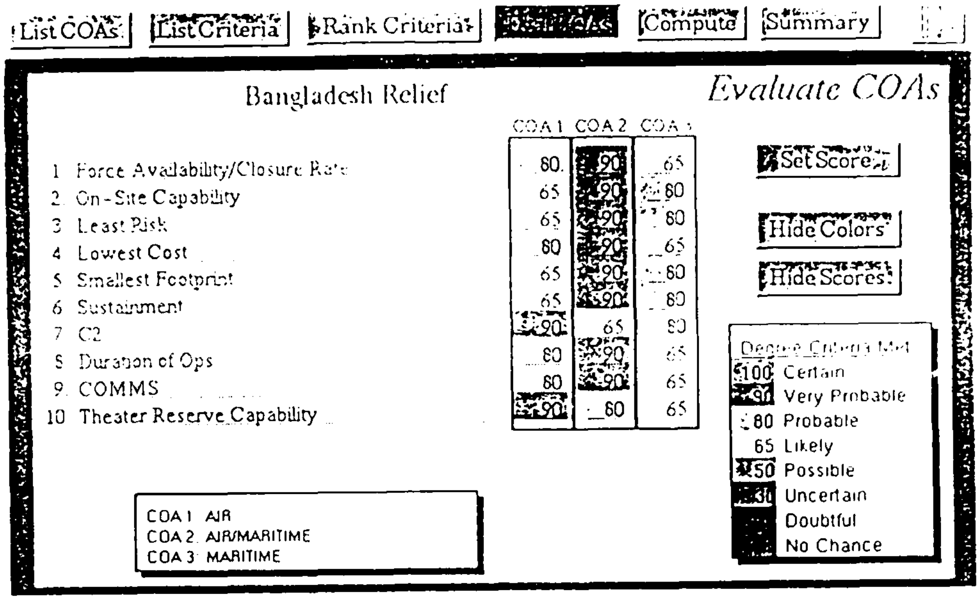

Fig. 10. **Evaluate COAs** Card

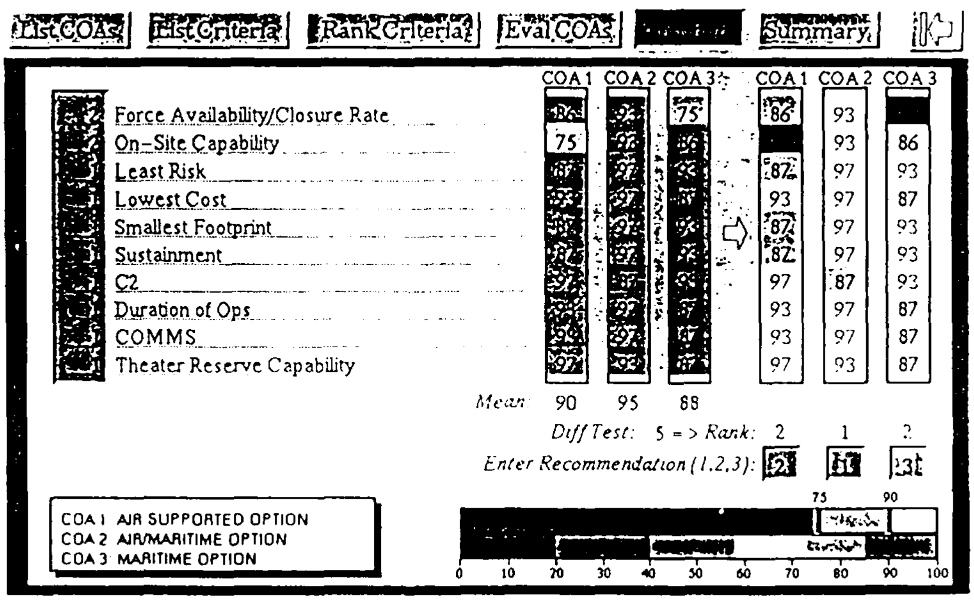

Fig. 11. **Compute** Card

Once the **Evaluate COAs** card is filled out, the user can select the **Compute** card which shows the results of the fuzzy method for combining the evaluation of the criteria with their importance. These results are shown in the three columns on the left. Below the columns are the means of the scores. These means are to be interpreted as the probability that "most criteria" will be met. For instance, the

probability that COA1 meets most criteria is 90%. The ranking of the COAs is determined using the standard statistical difference test with a significance of 50%. That is, the test determines whether there is at least a 50% probability that the difference in rank did not occur by chance, given the distribution of scores in the matrix. In the example shown the difference test statistic is 5. Since the mean of COA2 is 5 points greater than the mean of COA1 (i.e. 95% vice 90%), COA2 is ranked first while COA1 is ranked second. Since the difference between COA1 and COA3 is not greater than nor equal to 5, COA3 is also ranked second. That is, there is a 50% probability that COA2 should be ranked better than COA1 or COA3, but there is less than 50% probability that COA1 should be ranked better than COA3. Below the computed rank of the COA is a place for the user to enter his own rank recommendation, which can agree or disagree with the computed ranking.

In the lower right corner is a color scale which allows the user to reduce the 8 color scale to a 3 color scale. The user has selected 75% and 90% as the boundaries between the three colors.The three colors are green, yellow and red meaning good (no risk), indifferent (some risk) and bad (high risk). The colors green, yellow, red have been converted to white, grey, black for purposes here. This 8 to 3 color transformation is shown going from the left three columns to the right three columns. These three columns summarize the evaluation. The results are shown in the **Summary** card, Figure 12.

The **Summary** card is the COAST version of the COA Selection Matrix. The three COAs are evaluated against each criterion using the three color scheme. The recommended ranking of the COAs are shown at the bottom and the relative importance of the criteria are indicated by stars on the left. Recall that the first two criteria are considered more important than the rest.

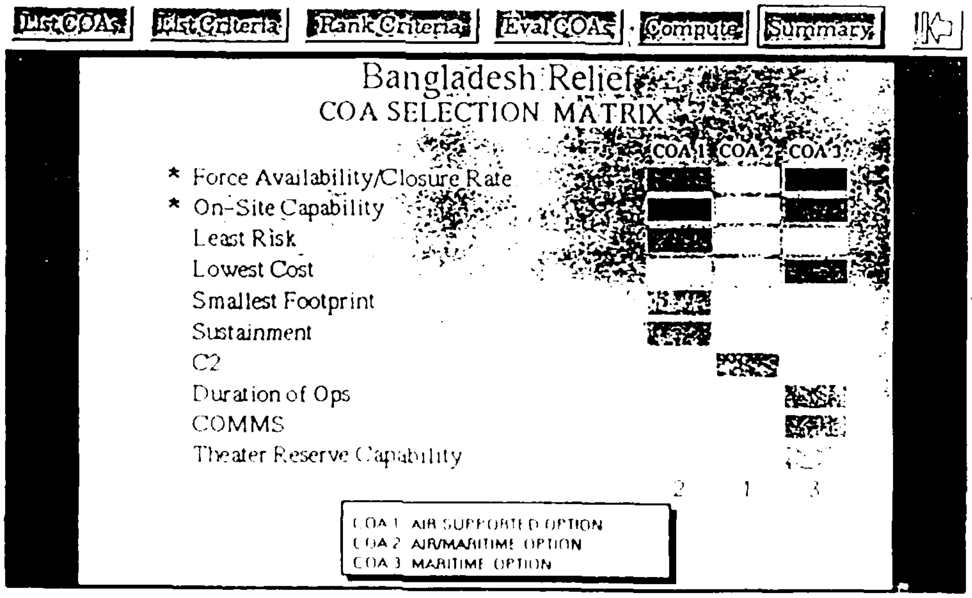

Fig. 12. **Summary** Card

THE WEIGHTED-SUM SELECTION MATRIX

The COA Selection Matrix in Figure 12 is to be compared with a corresponding weighted-sum Selection Matrix shown in Figure 13. In Figure 13 the COAs are ranked against the criteria with scores of 1, 2 or 3. The first two criteria are given twice the weight of the remaining criteria. These scores are added and the result is shown at the bottom. The scores in Figure 13 are intended to be comparable in terms of results to those in Figure 12.

BANGLADESH RELIEF

COA SELECTION MATRIX

	COA 1	COA 2	COA 3
FORCE AVAILABILITY / CLOSURE RATE	4	6	2
ON-SITE CAPABILITY	2	6	4
LEAST RISK	1	3	2
LOWEST COST	2	3	1
SMALLEST FOOTPRINT	1	3	2
SUSTAINMENT	1	3	2
C2	3	1	2
DURATION OF OPS	2	3	1
COMMS	2	3	1
THEATER RESERVE CAPABILITY	3	2	1
TOTAL	21	33	18

Fig. 13. Weighted-Sum Selection Matrix

The primary difference between the weighted-sum and fuzzy logic result is seen within the matrix. In the weighted-sum version it appears that COA2 is the better choice because it satisfies the two most important criteria best (i.e. scores of 6). In the fuzzy logic result, Figure 12, it appears that COA2 is preferred because it not only satisfies most criteria best, but because COA1 and COA3 have obvious weaknesses. That is, COA1 does not support On-Site Capability and COA3 does not support Force Availability/Closure Rate. These weaknesses in COA1 and COA3 are not evident in Figure 13. The conclusion to be reached is that the weighted-sum shows the strengths of a COA but fuzzy logic shows both strengths and weaknesses with equal emphasis.

It is also important to note that weighted-sum scores have no meaning other than relative scoring of the specific COAs in the Matrix. The fuzzy logic computed probabilities, on the other hand, are normalized measures of success. This means they can be used to meaningfully compare different missions with different selection criteria.

TECHNICAL BACKGROUND

Normative decision theory postulates decision making as an act of rational choice. Given a set of possible choices for a given situation, the optimal choice is the one which meets a set of selection criteria "best". Typically, "best" is determined by utility analysis, the weighted-sum method being the most commonly used version. The advantage of the weighted-sum is it allows users to express their preferences in a simple, easily understood way. The disadvantage is it has no substantive interpretation.

Another approach, probabilistic reasoning, allows rigorous calculation of the probability that a particular decision is the correct one. This approach has substantive interpretation as the good news. The bad news is it requires the user to determine (1) the probabilities that the criteria are met by a given decision choice, (2) the conditional probabilities quantifying the dependence of a successful decision outcome on meeting each criterion, and (3) the dependence between criteria. This implies a well defined problem space which is most often not the case.

An important enhancement of the probabilistic model uses fuzzy sets to represent subjective criteria and incomplete information about a situation. [Zadeh & Bellman] In many ways, fuzzy reasoning occupies a middle ground between probabilistic reasoning and utility analysis. Fuzzy logic has the advantages that it approximates probabilistic reasoning in a tractable way and uses natural language evaluation which is straightforward and intuitively appealing. Humans deal naturally with subjective or fuzzy information. Typically we speak of tall men in easily understood conversation, although in actual fact, we cannot precisely define what a tall man is. Likewise military command and control, by its nature, deals extensively with imprecise knowledge and subjective goals. The state of a battlefield situation is usually not well known. There is never enough information or time to completely analyze a situation in order to make a decision. Yet humans tend to perform reasonably well under such circumstances, arriving at good decisions in spite of ambiguity and confusion.

On the other hand, the volume of information and the pace of operations of modern warfare preclude the time consuming and man intensive processes of the past. In addition, despite their best efforts, human feelings and preferences remain inconsistent and intransitive, often leading to judgmental errors. The battlefield of the future has an overriding need for computerized information and decision support systems which support rapid, reliable and effective assimilation of timely information for planning, decisions and command action.

FUZZY LOGIC

[Zadeh] formulated the initial statement of fuzzy set theory. Fuzzy set theory is based on a recognition that certain sets have imprecise boundaries. Typically we speak of tall men or expensive homes. Membership in such sets or classes of objects is not characterized by either/or, but are sets in which membership can be adequately considered in terms of degrees. Fuzzy logic is concerned with the formal principles of approximate reasoning, with precise reasoning viewed as a limiting case.

Natural language evaluation is an important aspect of fuzzy reasoning and COAST. Table 1 illustrates a typical linguistic likelihood scale which has been derived from extensive surveys. In COAST, the user is asked to specify the degree that a given COA satisfies a selection criterion using a version of this scale.

no chance	0.0
unlikely	0.1
doubtful	0.2
uncertain	0.3
possible	0.4
moderate risk	0.5
significant chance	0.6
likely	0.7
probable	0.8
very probable	0.9
certain	1.0

Table 1. A Linguistic Likelihood Scale

The primary fuzzy operation of concern here is the notion of exponentiation as introduced by [Zadeh]. It is used in COAST to express the importance of the criteria to mission success. In possibilistic terms, it is used to approximate the conditional dependence of mission success on the individual criterion. Let p_j represent the probability that criterion j is satisfied by a particular COA. Let P_j be the probability representing the dependence of mission success on criterion j. If criterion j is essential to the mission then $P_j = p_j$. If criterion j has no importance to mission success, then $P_j = 1$ no matter what the value of p_j. That is, mission success is certain, $P_j = 1$, insofar as criterion j is concerned because mission

success does not depend on criterion j. In general, the exponentiation operation as defined by Zadeh states that

$$P_j = p_j^{I_j} \qquad \text{where } 0 \le I_j \le 1$$

In this formula I_j is the importance of criterion j to mission success. If criterion j is essential, $I_j = 1$. If criterion j has no importance, $I_j = 0$. In COAST the user is allowed to define a criterion as important, very important or essential. In fuzzy logic, these terms are represented by the exponentiation operation as follows:

$$P_j = p_j^{3/3} \quad \text{if criterion j is essential}$$

$$P_j = p_j^{2/3} \quad \text{if criterion j is very important}$$

$$P_j = p_j^{1/3} \quad \text{if criterion j is important}$$

In the terminology of Zadeh, $I_j < 1$ reduces grade of membership but in such a manner that large membership values p_j are reduced much less than small ones. In the extreme of large membership, $p_j = 1$ resulting in $Pj = 1$ no matter what value I_j assumes.

COA SELECTION METRIC

An overall probability of mission success, Ps, can be computed by combining the probabilities of satisfying the individual criterion. If the dependence between criterion is known, it can be accommodated in a probabilistic combination calculation. If the criteria are independent, the probability that all criteria are met is the intersection of the probabilities

$$P_s = \prod_j p_j^{I_j}$$

If all the criteria are dependent, the probability that all criteria are met is the minimum of the probabilities

$$P_s = \min_j \{ p_j^{I_j} \}$$

More complicated dependencies can be treated in a similar manner.

As mentioned in the OVERVIEW, a more important issue is to decide what is meant by the probability of mission success in the context of satisfying selection criteria. Should it be the probability that "all criteria are met"? After some consideration, it was decided the probability that "most criteria are met" is the

preferred metric, primarily because it has properties similar to the weighted sum currently in use. A strict calculation of this probability is complicated and runs counters the spirit of fuzzy logic. To this end, the mean of the individual probabilities for the set of criteria was found to be a good approximation to the probability that "most criteria are met". Thus the COA selection metric or estimate of the probability of mission success is

$$\text{Selection Metric} = P_S = \mu = \frac{1}{N} \sum_j p_j^{lj}$$

The standard deviation of the individual probabilities about their mean is used to determine the statistical significance of mean probability differences between COAs.

$$\text{Significance Metric} = \text{T-Test} = \frac{\mu 2 - \mu 1}{2\,\sigma}$$

In this way, not only the ranking, but also the significance of the ranking of the COAs is determined.

PAIRWISE CRITERIA EVALUATION

The next problem discussed is that of obtaining a scale on which we can measure the importance of each criterion. One way is the straightforward ranking of the criteria. Ranking is a simple way to express preferences. However it is well known that it may hide user uncertainty and bias. A second method is provided in COAST which is intended to overcome this drawback. It is the pairwise comparison method developed by [Saaty]. It allows an overall ranking of criteria to be determined from simpler pairwise comparisons. It also allows the consistency of the results to be measured and it identifies those pairwise evaluations which are inconsistent with the overall pairwise evaluation. Its disadvantage is that for n criteria, n(n-1)/2 paired comparisions must be made. In COAST we limit the number of criteria compared pairwise to 6, resulting in a maximum of 15 pairs to compare. In COAST the user has to make an initial ranking of the criteria, in order to identify up to 6 of the most important criteria for the purpose of pairwise evaluation.

Saaty's procedure for obtaining a ratio scale for a group of elements based upon a paired comparison of each of the elements has also been used by [Yager] to obtain the values of subjective probabilities from a decision-maker. For n criteria, we ask the decision-maker to compare the criteria in n(n-1)/2 paired comparisons. In particular, for each case where criterion i is more important that criterion j, a value a_{ij} is assigned from Table 2.

Level of importance	Definition
0	No importance over the other
1	Some importance over the other
2	Very important over the other
4	Absolute importance over the other

Table 2. Pairwise Comparison Scale

Having obtained the above judgments an n x n matrix B is constructed so that

$$
\begin{aligned}
&(1)\ b_{ii} = 1; \\
&(2)\ b_{ij} = a_{ij},\ i \neq j; \\
&(2)\ b_{ij} = 1/b_{ji}.
\end{aligned}
$$

[Saaty] shows that the eigenvector corresponding to the maximum eigenvalue, λ_{max}, of B is a cardinal ratio scale or absolute ranking of the criteria. The measure of inconsistency derived by [Saaty] is

$$[(\lambda_{max} - n)/(2n-2)]^{1/2}$$

[Larsen & Dillard] derive an algorithm which identifies the most inconsistent pairs in the matrix.

CONCLUSION

Fuzzy sets provide a fertile tool with which to investigate the multiple-criterion decision problems. One reason for this is the fact that by using a fuzzy set we are dealing in a very universal concept of "the degree to which an alternative satisfies a criterion", something which can be understood for any criterion. A second reason is that fuzzy sets provide a mathematical structure for manipulating vague ideas which become very common in complex multiple-criteria problems.

Fuzzy evaluation with COAST provides a measure of the probability of mission success. This is an indication of overall risk in the sense that the probability of mission failure is the complement of the probability of mission success. More importantly, probability of mission success is a normalized estimate which can be used to meaningfully compare different missions with different evaluation criteria. These are benefits of fuzzy reasoning which utility analysis does not provide. Utility analysis can determine the strengths of a COA but fuzzy logic shows both strengths and weaknesses with equal emphasis.

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